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FEASIBILITY STUDY TOWARD DEVELOPMENT OF
RADIATION RESISTANT SOLAR CELL

Prepared for
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Prepared by
S. Kaye
S. Kaye

Approved by
for B. Kagan
M. B. Prince, Manager
SOLID STATE DIVISION

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ELECTRO-OPTICAL SYSTEMS, INC. - PASADENA, CALIFORNIA

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1. INTRODUCTION

This report presents the results of the last four months' study designed to show the feasibility of producing radiation resistant silicon solar cells by the use of a graded base structure.

Methods of fabrication of both n on p and p on n graded base cells are discussed and the results of efficiency measurements at sea level and on Table Mountain are presented.

The results of bombarding the cells with 1 Mev electrons are shown and are compared with the results by bombarding n on p cells having a uniform base region of 25 ohm cm resistivity.

The results of experiments designed to measure the presence of an electric field in the base region of the graded base cells by carrier transit time measurements are given.

The results of theoretical work are given.

Author

2. DEVICE THEORY

A start has been made on a rigorous analysis of the effects of electric field in the base region of the cell. The approach we have used is that given by Kleinman[1].

We have investigated the solutions to the transport equation

$$D \frac{d^2n}{dx^2} - \frac{n}{\tau} - \mu E \frac{dn}{dx} + \int_0^{\lambda G} N(\lambda)\, \alpha(\lambda) e^{-\alpha x} d\lambda = 0 \qquad (1)$$

for the case of an electric field in the base region. (Note: The notation used is that of Kleinman). Unfortunately this case was not considered by Kleinman in his analysis.

In determining the boundary conditions for the solution of the equation, it was assumed that at the junction the minority carrier density was zero and that the cell thickness was large.

Since an analytic solution cannot be obtained due to the nature of the functions $N(\lambda)$ and $\alpha(\lambda)$ the problem was set up for solution on an IBM 1620 computer. The collection efficiency of carriers generated in the base region of the cell is shown in Figure 1 as a function of diffusion length ($L = \sqrt{D\tau}$) for four values of field in a cell with a junction depth of 0.5μ. The range of diffusion lengths investigated was 5-200μ and the fields were 0, 20, 40, 100 and 200 volts/cm.

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[1] D.A. Kleinman - Considerations on the Solar Cell, B.S.T.J. 40, p. 85, January 1961.

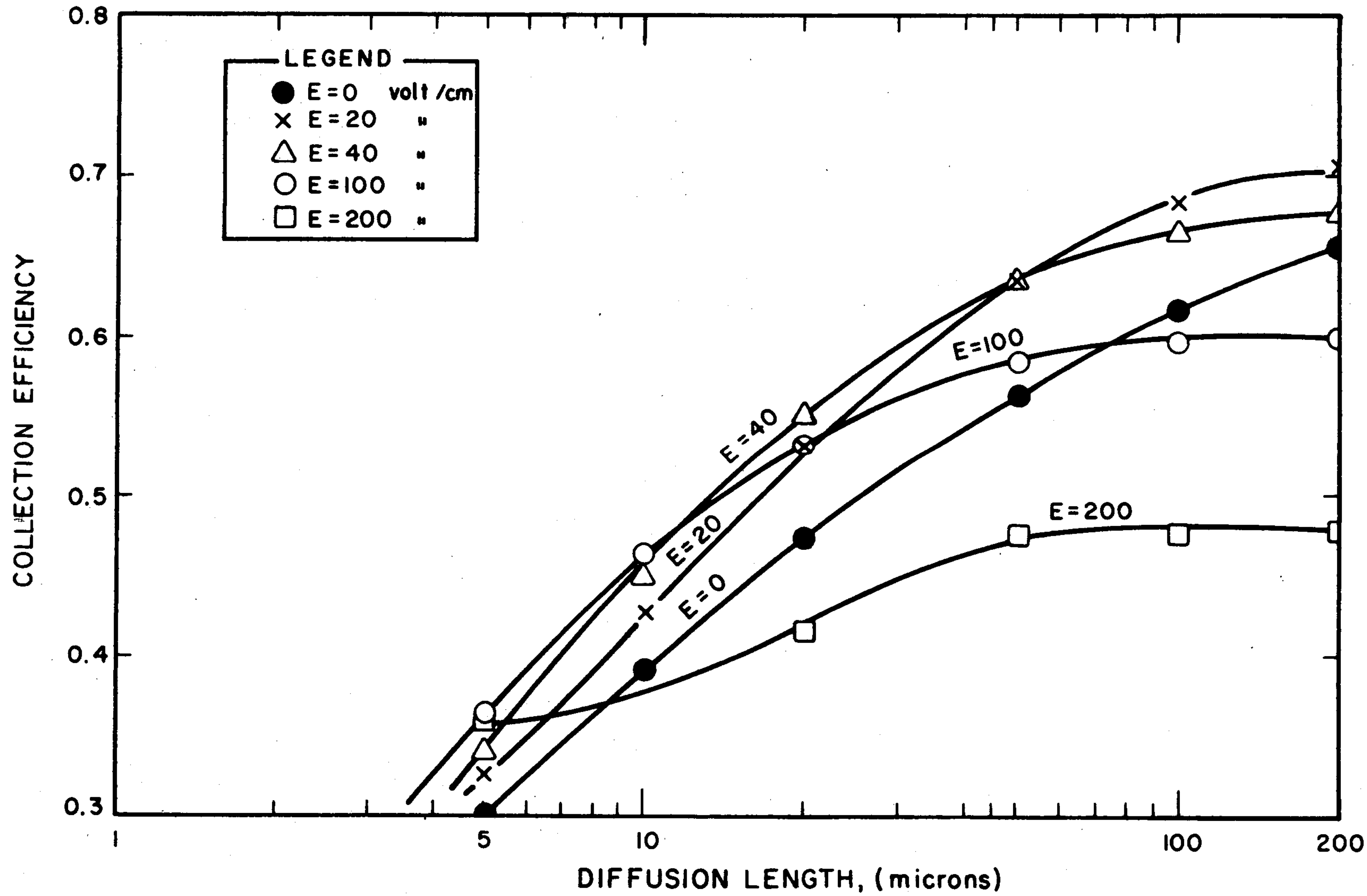

FIG. 1 COLLECTION EFFICIENCY OF CARRIERS GENERATED IN BASE REGION BY INCIDENT SOLAR SPECTRUM AS A FUNCTION OF DIFFUSION LENGTH

It may be seen that the calculation leads to the somewhat puzzling conclusion, that for longer diffusion lengths increasing fields decreased the collection efficiency! After careful checking we have been unable to discover any errors in the mechanics of the calculation and it must therefore be assumed that either the result is in fact valid or that our choice of boundary conditions is invalid.

3. CELL FABRICATION

3.1 N on P Cells

Fabrication of n on p cells has continued using the same processes as described in earlier reports. By improvements of measuring techniques, it has proved possible to obtain meaningful measurements of the impurity distribution in the base region subsequent to the deep base diffusion. Figure 2 shows the results of such a measurement using the normal paint-on technique which has been described. It will be seen that the surface concentration is approximately 3×10^{19} cm^{3}. This result is typical of those obtained on a number of different runs. An attempt was made to determine the effects of increased boron concentration. The higher concentration was obtained by increasing the concentration of B_2O_3 in the paint which is applied to the surface as the dopant prior to diffusion. Figure 3 shows the results of the impurity profile taken after such a diffusion. It will be seen that the surface concentration has increased by approximately an order of magnitude. It is not possible to tell whether the apparent point of inflection in the curve really exists or is due to difficulties of measurement.

It was not possible to fabricate cells from this more heavily doped material due to the fact that the very high concentration of boron caused considerable crystalline strain, and it was not possible to obtain smooth etched surfaces on the slices which had been subjected to this diffusion treatment.

From the results shown in Figures 2 and 3 the electric field in the base region of the cell was calculated. Due to the uncertainties

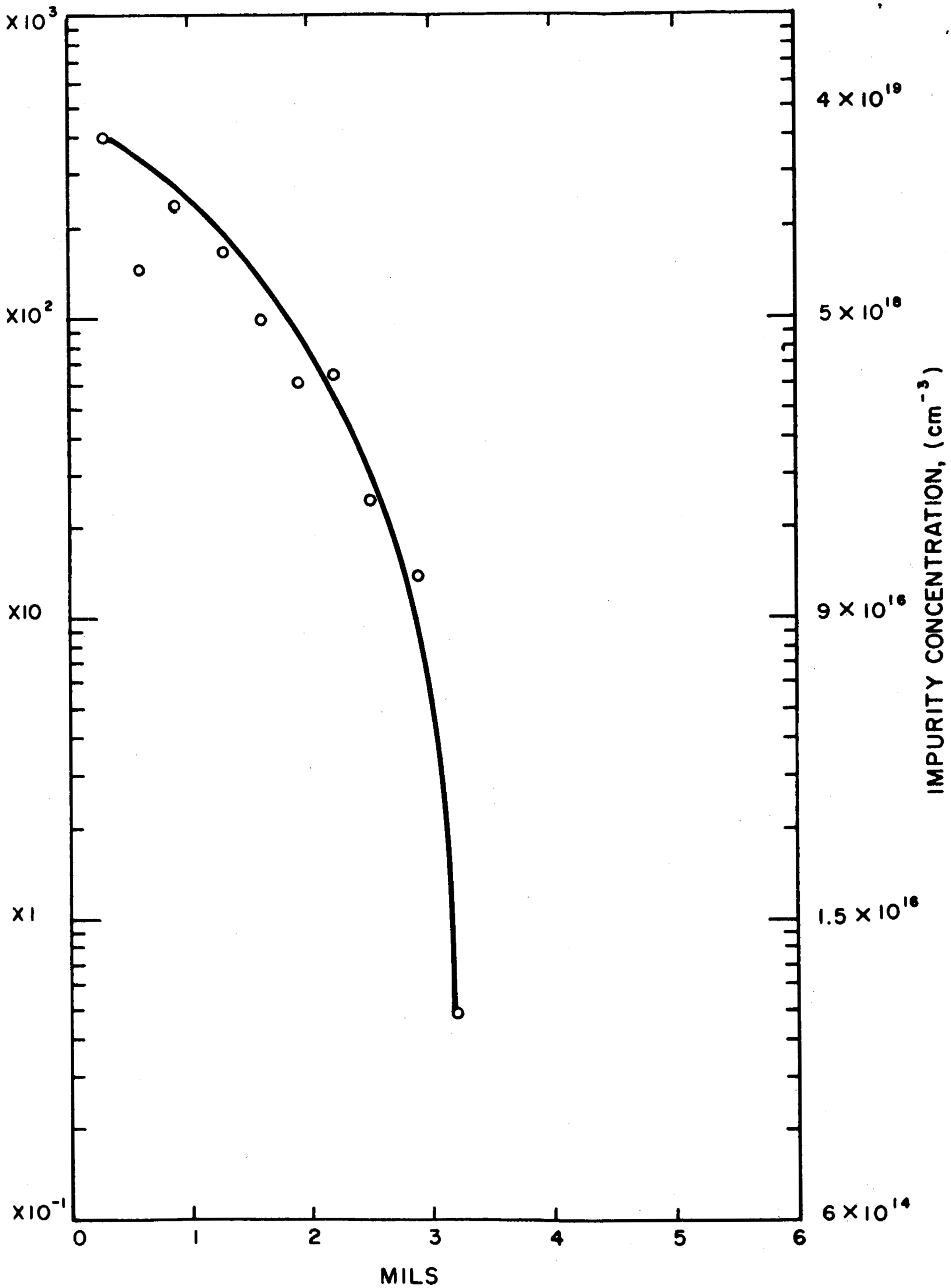

FIG. 2 BASE IMPURITY DISTRIBUTION

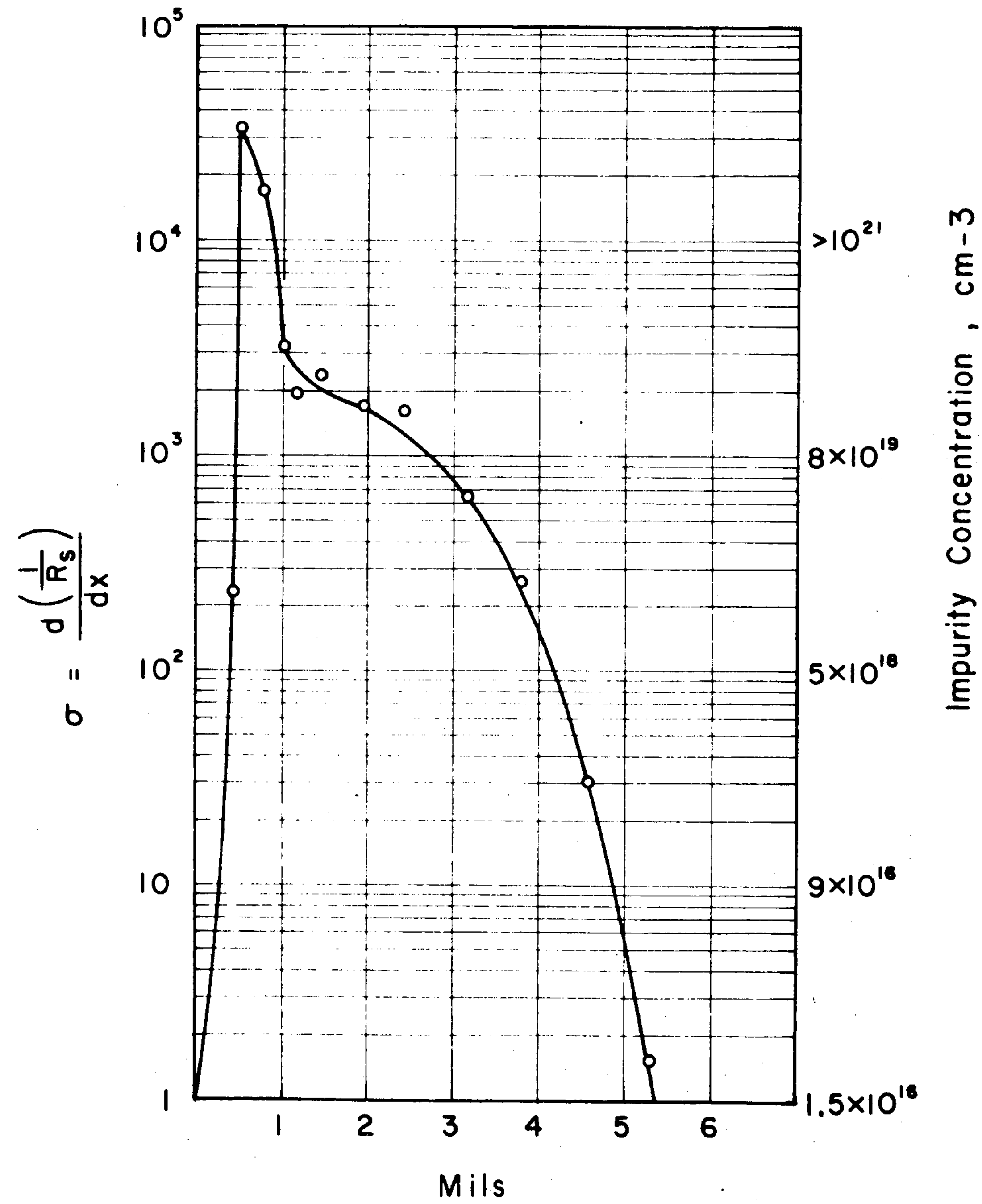

FIG. 3 BASE IMPURITY DISTRIBUTION

in the measurements this calculation was at best an approximate estimate, and showed that in the case of the higher doped cell, an increase in the average electric field in the base region by at most 20% was obtained. Since this is a marginal increase, it was decided not to pursue these experiments further.

3.2 P on N Cells

As a result of a suggestion by the technical monitor, it was decided to fabricate graded base p on n cells and subject them to irradiation. The object of the experiment was to determine whether graded base p on n cells exhibited an improvement in performance compared with uniform base p on n cells. If this were so it would be confirmatory evidence as to the validity of the graded base concept in producing radiation resistance in solar cells.

The processes required for the fabrication of graded base p on n cells were therefore developed. These processes are essentially similar to those used for the n on p cells with the appropriate interchange of dopants for the diffusion processes. Starting material is 15 ohm cm N-type silicon. The graded base region was produced by pre-depositing phosphorous onto the slices. A P_2O_5 source was held 300°C and the slices were held at a temperature of 1050°C for a period of thirty minutes. The dopant was carried to the slices in a stream of dry nitrogen. The pre-deposited layer was then driven in by diffusion at a temperature of 1250°C for 100 hours. Impurity profiles were determined and representative examples are shown in Figures 4 and 5. Slices were then lapped to a thickness of 4 mils and the p-type region was produced by carrying out a diffusion at a temperature of 1050°C for 12 minutes using B_2O_3 as a source. Subsequent processing was identical to that described earlier for the n on p type cells.

One batch of p on n cells was fabricated and gave efficiencies between 8 and 9%. These cells were submitted to electron radiation and the results will be discussed in a subsequent section.

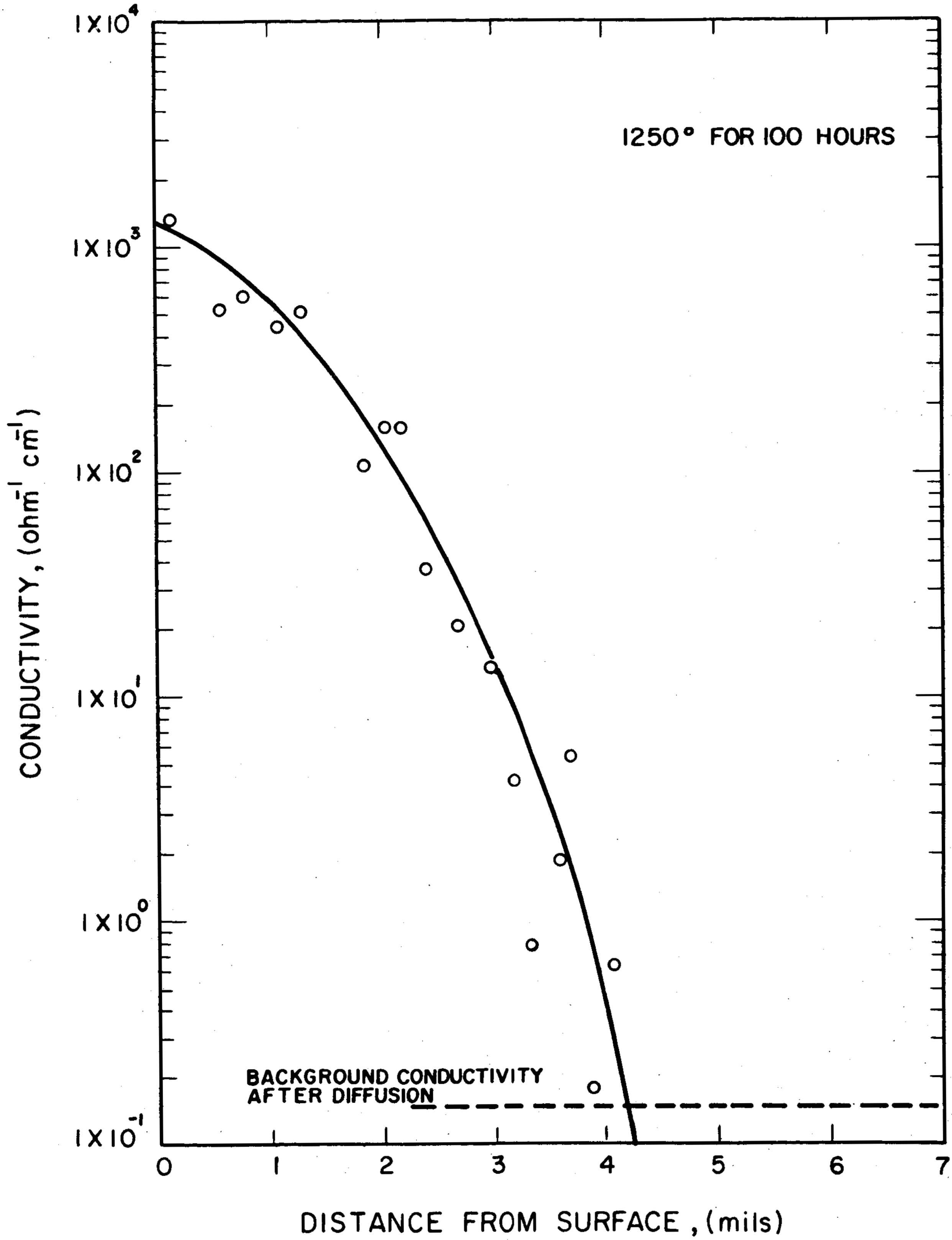

FIG. 4 CONDUCTIVITY VS DISTANCE FROM SURFACE OF PHOSPHORUS DIFFUSION INTO 15 Ωcm N TYPE SILICON

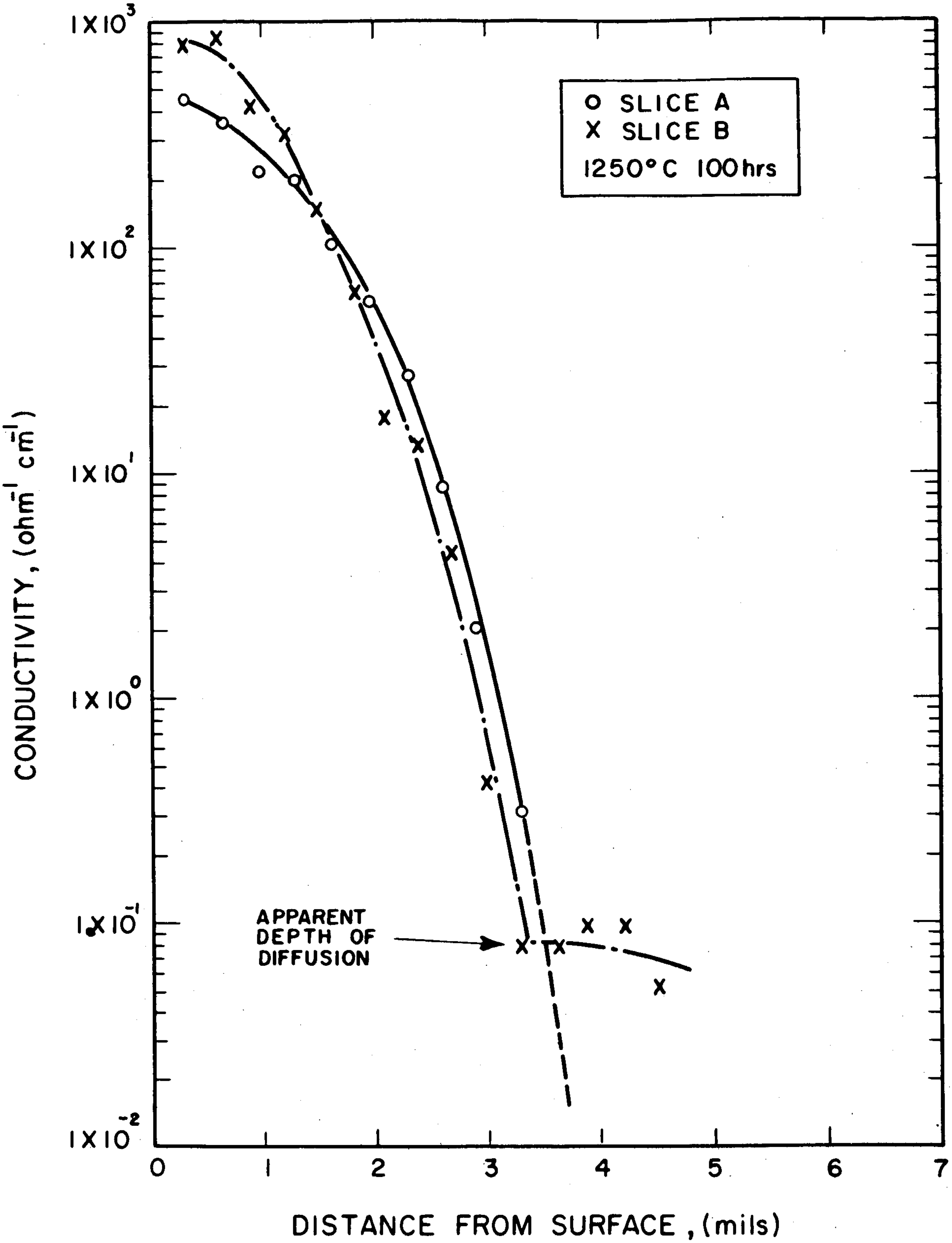

FIG. 5 CONDUCTIVITY VS DISTANCE FROM SURFACE OF PHOSPHORUS DIFFUSION INTO 15 Ωcm N TYPE SILICON

4. CELL TESTING

4.1 Transit Time Experiments

An experiment was carried out designed to measure the transit time of carriers injected into the back of a cell. It was expected that by this means it would be possible to verify the existence of an electric field in the base region of the cell driving the injected minority carriers towards the junction. If the case of a δ function of injected carriers is considered, it can be shown that the transit time t for the injected carriers to move a distance W is given by Eq. (1)[2].

$$t = \frac{W^2 \pi}{4D} \qquad (2)$$

where

D is the diffusion coefficient of the injected carriers.

For electrons in a layer of p-type silicon 100 microns thick, this transit time is 2.6 microseconds. Since it is expected that the electric field introduced into the base region by the diffusion of impurities will reduce the transit time to 1 microsecond or less[3]. It should be possible to distinguish between the field and non-field case by injecting carriers into the back of the cell and measuring the time required for them to arrive at the junction. The method used of injecting the carriers was to use photo-injection, and the setup is shown diagrammatically in Figure 6. The cell under

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[2] A. K. Jonscher "Principles of Semiconductor Devices Operation", p.68, Wiley, 1960.

[3] EOS Progress Report for November 1961, 2080-ML-1

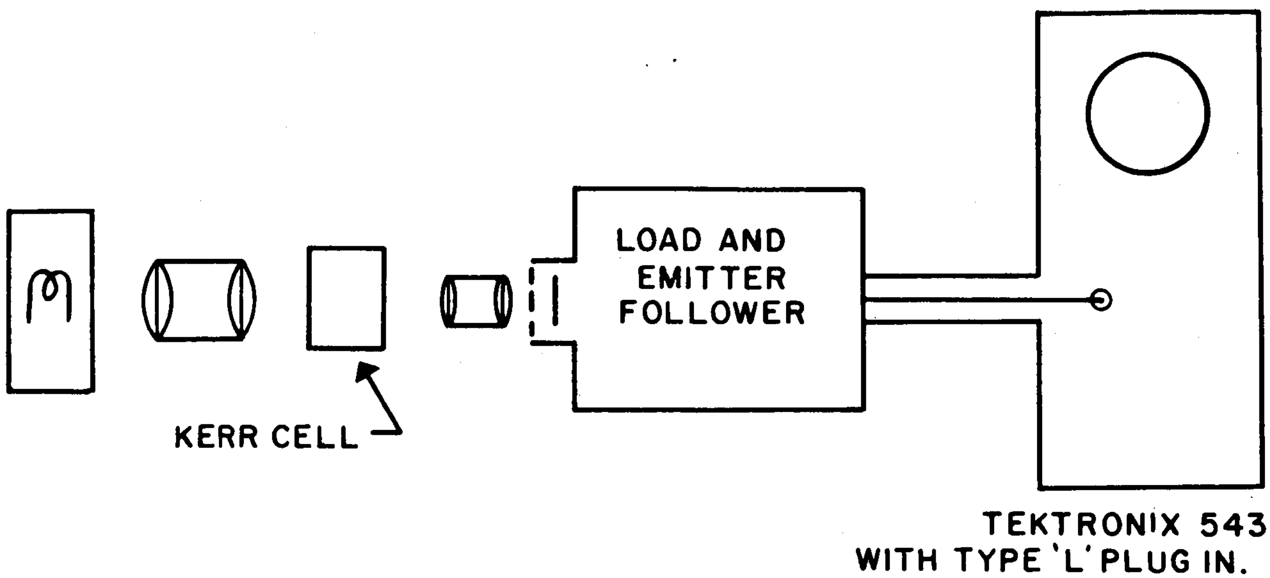


FIG. 6 DIAGRAM OF TEST SETUP

test was illuminated with a pulse of light, 1 microsecond long using a Kerr cell shutter as a means of producing the pulse. The device to be tested was prepared by taking a portion of a solar cell and etching a mesa approximately 2 mm in diameter on the front surface of the cell. Pressure contacts were made to this diode structure which could be illuminated either from the front or the back by reversing the diode in its holder. The measurement circuit is shown in Figure 7. Due to the fact that the Kerr cell required 35 KV pulses to operate it, it was necessary to shield the complete circuit shown in Fig. 7 very carefully in order to prevent electrostatic pickup. Figure 8 is a photograph of the complete test setup in use.

4.1.1 Results

Figures 9 through 13 are photographs of the oscilloscope traces made under various conditions of illumination of both graded base and control cells. Figures 9, 10 and 11 were obtained on a mesa etched from a portion of a graded base cell. Figure 9 shows the trace obtained when the cell was illuminated with 1 microsecond pulse of light on its front surface. Figures 10 and 11 show the results obtained with the same specimen when it was illuminated from the back. In Figure 10 no filter was used, but in Figure 11, a Corning CS4-97 filter, which is a blue-green filter having zero transmission in the near infrared, was interposed in the optical path. It will be noticed that there is no difference in the general characteristic of the curve between Figs. 10 and 11. It will also be seen that the time required for the output voltage to reach its maximum value is independent of whether the cell is illuminated from the front or the back. It may be concluded that the measurement was not sufficiently sensitive to detect the transit time difference between back and front on the graded base cell. Figures 12 and 13 show the results of a similar experiment carried out on a specimen from a control or uniform base cell. In this

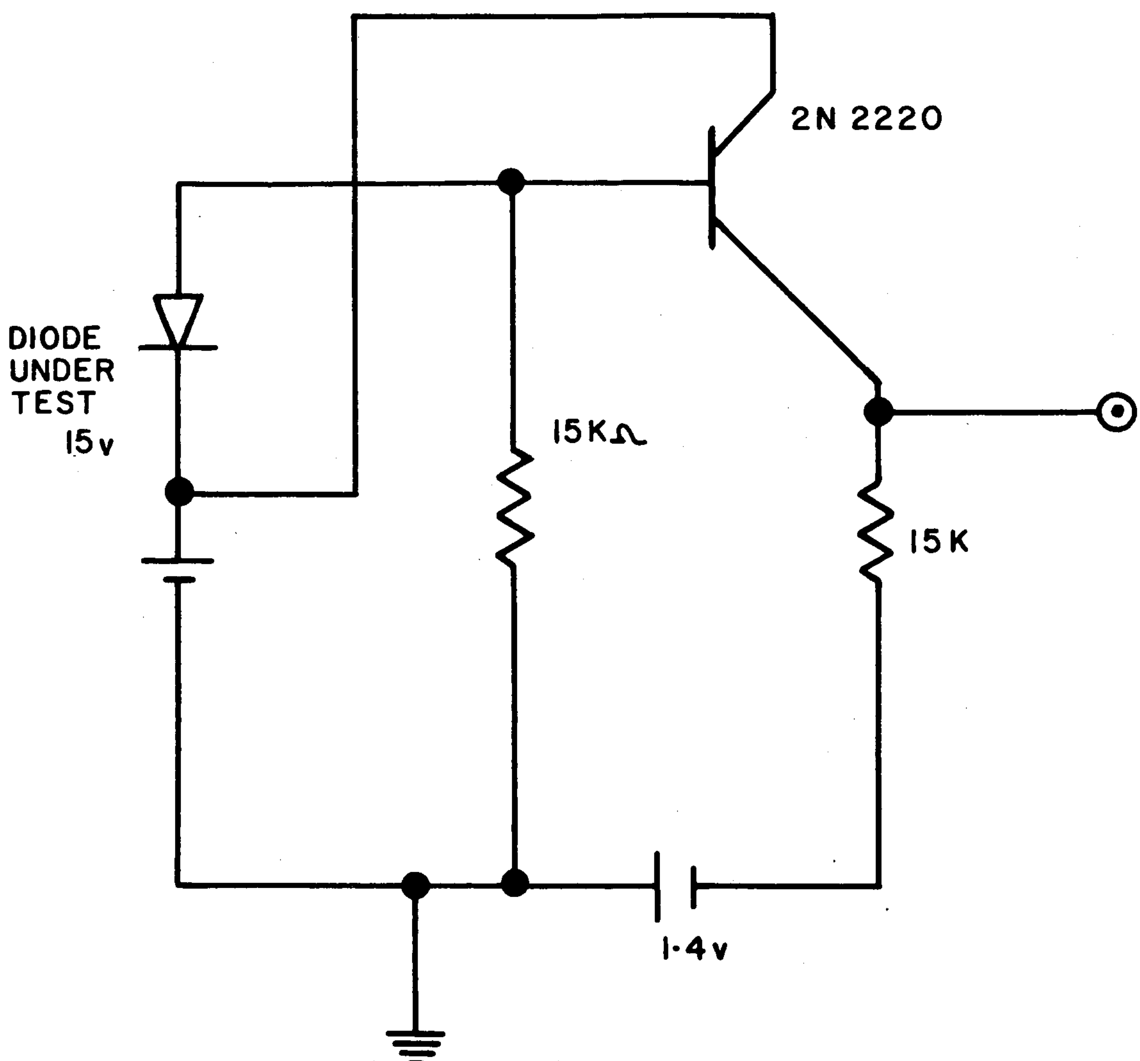


FIG. 7 DIODE TEST CIRCUIT

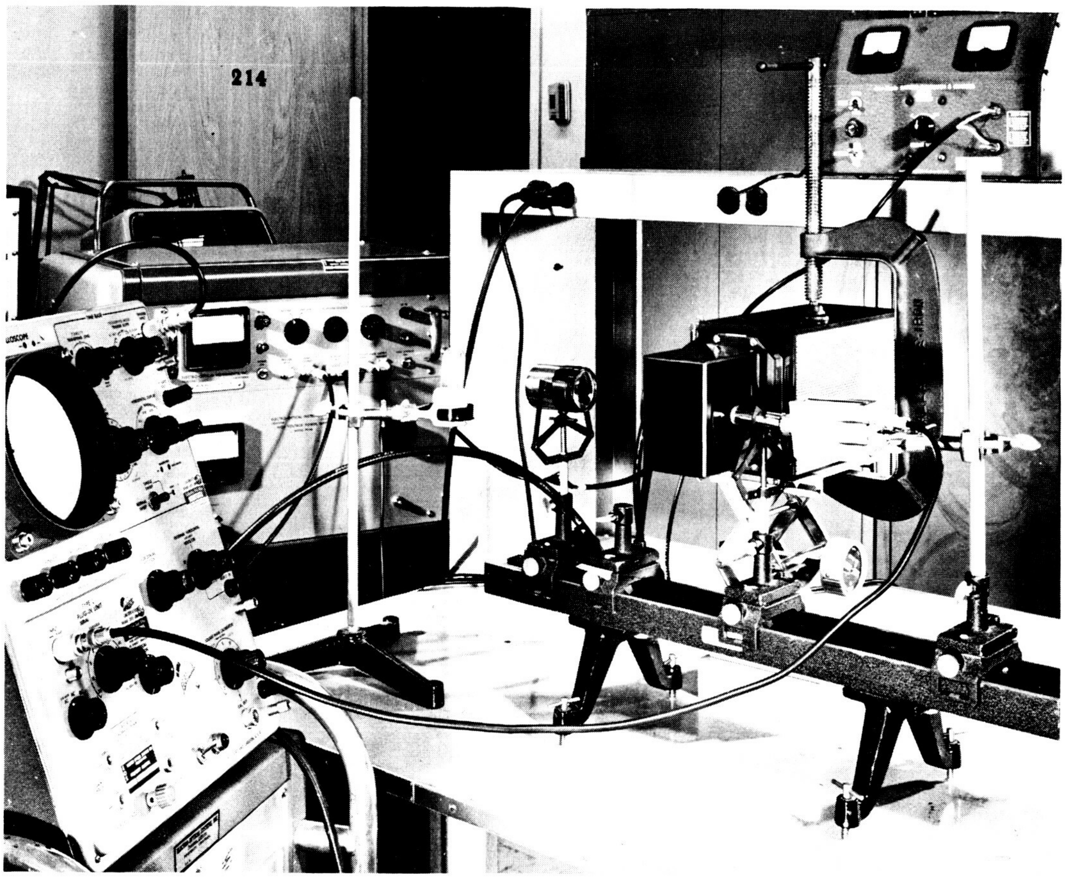
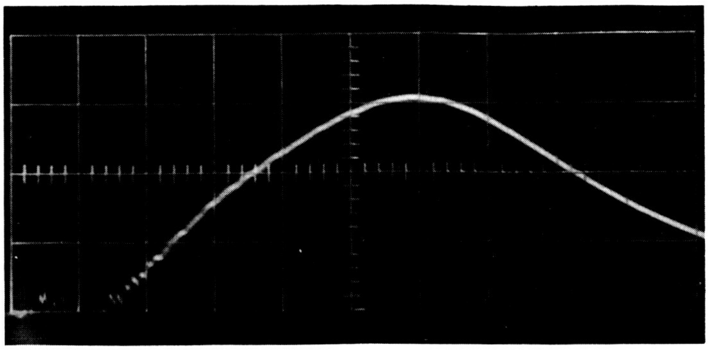
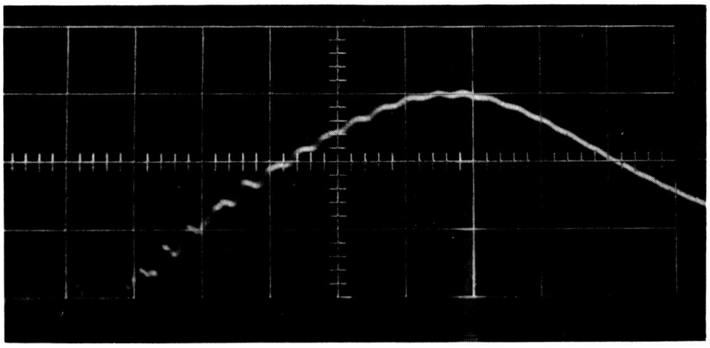


FIG. 8 TEST SETUP



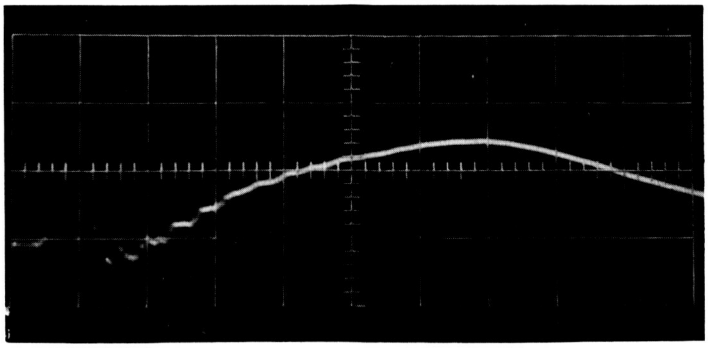
Vertical   .05 volts/division
Horizontal .2 μs/division

FIG. 9 GRADED BASE CELL ILLUMINATED FROM FRONT



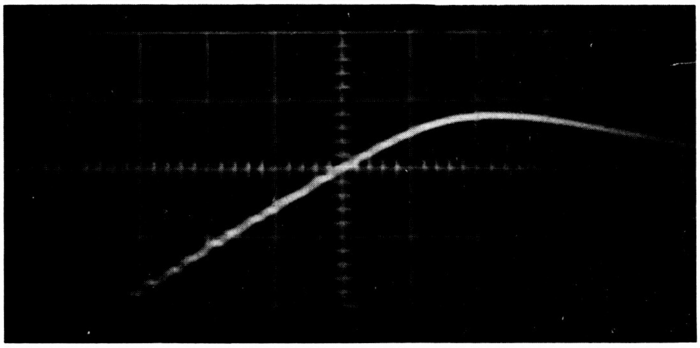
Vertical   .05 volts/division
Horizontal .02 μs/division

FIG. 10 GRADED BASE CELL ILLUMINATED FROM BACK (Unfiltered light)



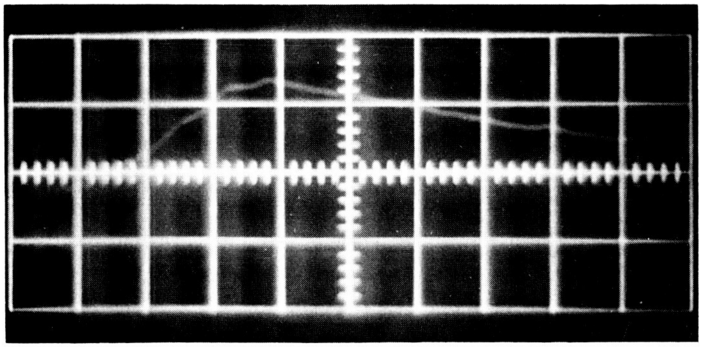
Vertical   .005 volts/division

FIG. 11 GRADED BASE CELL ILLUMINATED FROM BACK (Filtered light)



Vertical 0.2 volts/division
Horizontal 0.2 μs/division

FIG. 12 CONTROL CELL ILLUMINATED FROM FRONT (Unfiltered light)



Vertical .02 volts/division
Horizontal 0.5 μs/division

FIG. 13 CONTROL CELL ILLUMINATED FROM BACK (Unfiltered light)

4.2 Cell Efficiency Measurements

Large discrepancies were found between cell efficiency measurements made at STL under tungsten light and those made at Electro-Optical Systems, Inc., on the same cells in the sunlight. These discrepancies were too large to be explained by the difference in the spectral content of the light. An investigation was therefore made of the measuring setup at Electro-Optical Systems. It was determined that two causes were leading to error. First of these was that the subtended angle of the tube which collimated the light falling on the cell under test was different from the subtended angle of the collimation tube attached to the pyrheliometer. This was corrected as was the second fault which was shadowing of the cell by the contact jig. A modified jig was made which avoided this problem.

Fifty-five cells were measured in the modified setup. Of these, fifteen had efficiencies less than 9%, twenty-two had efficiencies between 9 and 10%, and twelve had efficiencies greater than 10%. Of these cells, nine were p on n having efficiencies in the 9 to 11% range. Forty-five cells which had previously been measured in sunlight in the Electro-Optical Systems parking lot were taken to Table Mountain and their efficiencies were measured on the 2nd of October. The average of the efficiencies measured in the parking lot exceeded that measured on the mountain by .027%. The standard error of this mean value was calculated and found to be .08%, thus applying a Student t test, a t value equal to .33 was found. This difference of mean values was therefore not significantly different from zero.

4.3 Irradiation N on P

During the past month three groups of cells were subject to 1 Mev electron radiation and Figures 14,15 and 16 show the short circuit current density as a function of the electron flux for the cells when they were illuminated with 2800°K light. Figures 17 and 18 show results on two other groups of cells. These results have been reported previously and are reproduced here for convenience of discussion. In each case the data has been plotted on the basis of a cell having a total area of 1 cm^2 with an active area of 0.8 cm^2. Figure 14 shows the results obtained on two groups of control cells and is shown in overlay form for ready comparison with the results shown in Figs. 15 through 18. These two groups were processed simultaneously on 25 ohm cm p-type silicon and have a uniform base region.

The object of obtaining these results was twofold. At the present time there has not been made available to us any published data on the radiation resistance of n on p cells fabricated on high resistivity material and tested under 2800°K illumination. It was decided therefore to prepare such cells having two thicknesses of base region, namely 12 mils which would be typical of normal cell construction, and 4 mils which is comparable with the thickness of the material used in the graded base cell. It is planned to make similar groups of cells on 1 ohm cm n-type silicon by identical processing in order that further comparative results may be obtained. The initial short circuit currents on the thicker batch of cells were considerably higher than those on the thin cells due to the fact that in the unirradiated condition the diffusion length in the thin cells is comparable with the cell thickness, thus the collection efficiency from the base region would be reduced leading to a lower short circuit current.

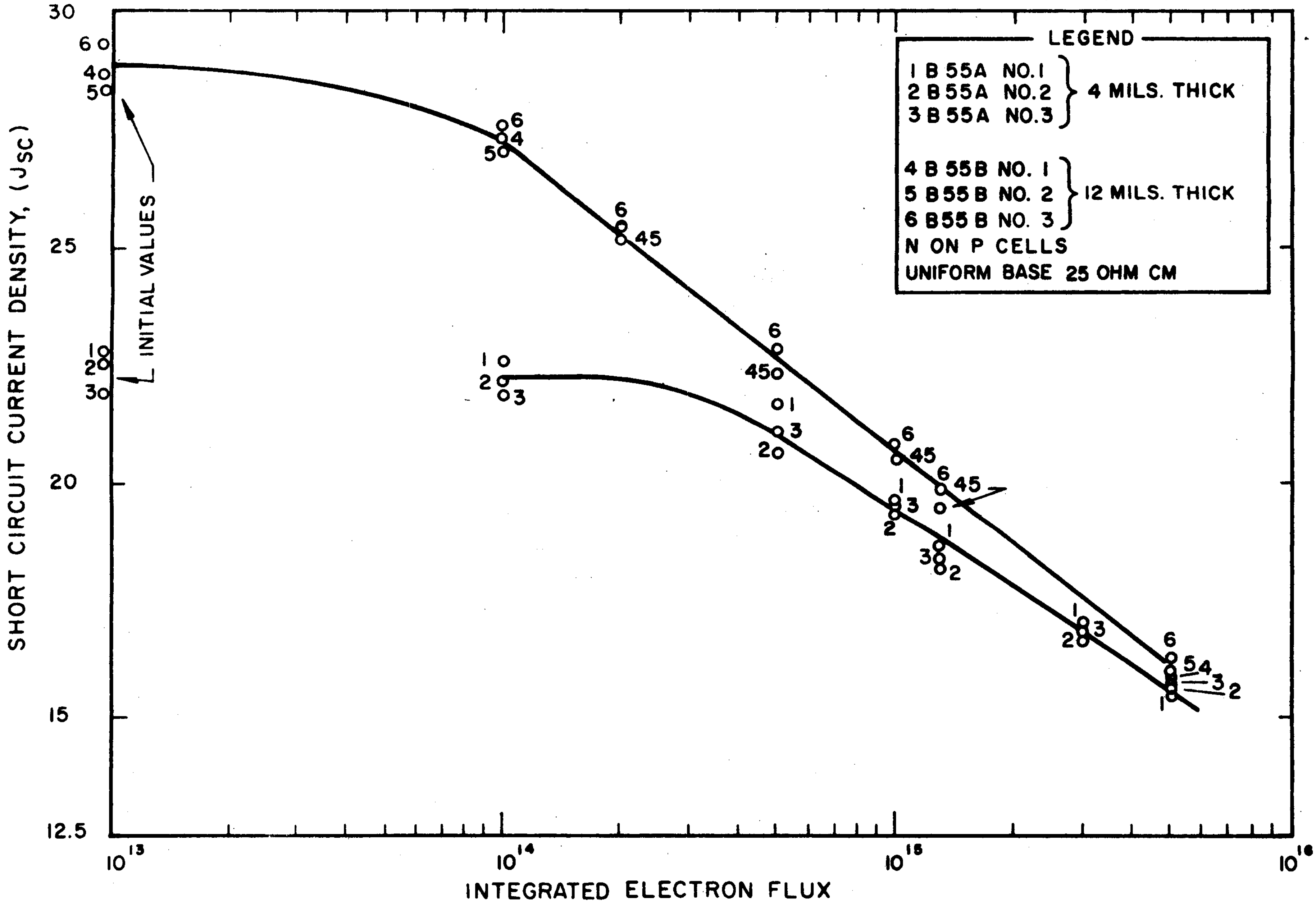


FIG. 14 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

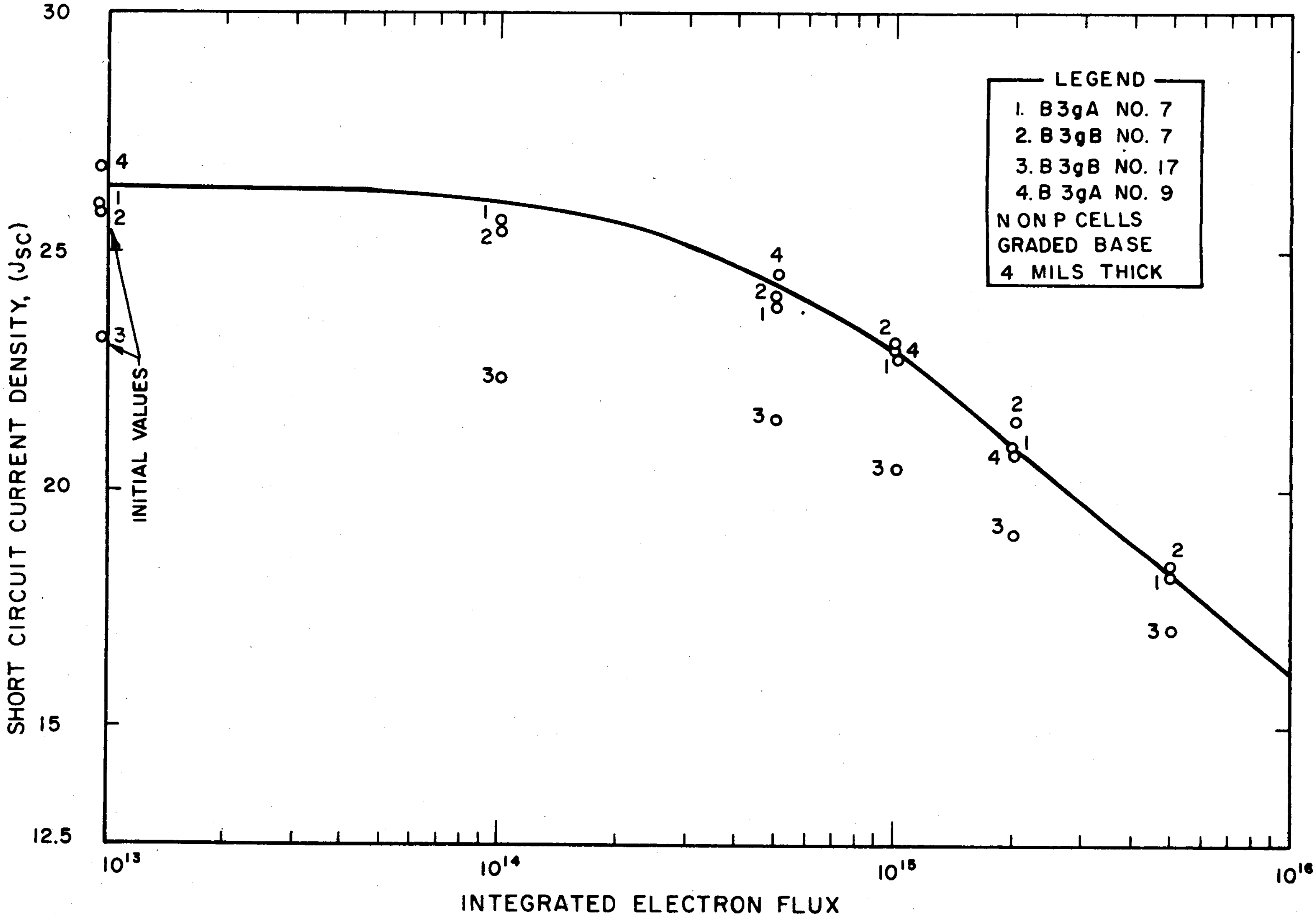


FIG. 15 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

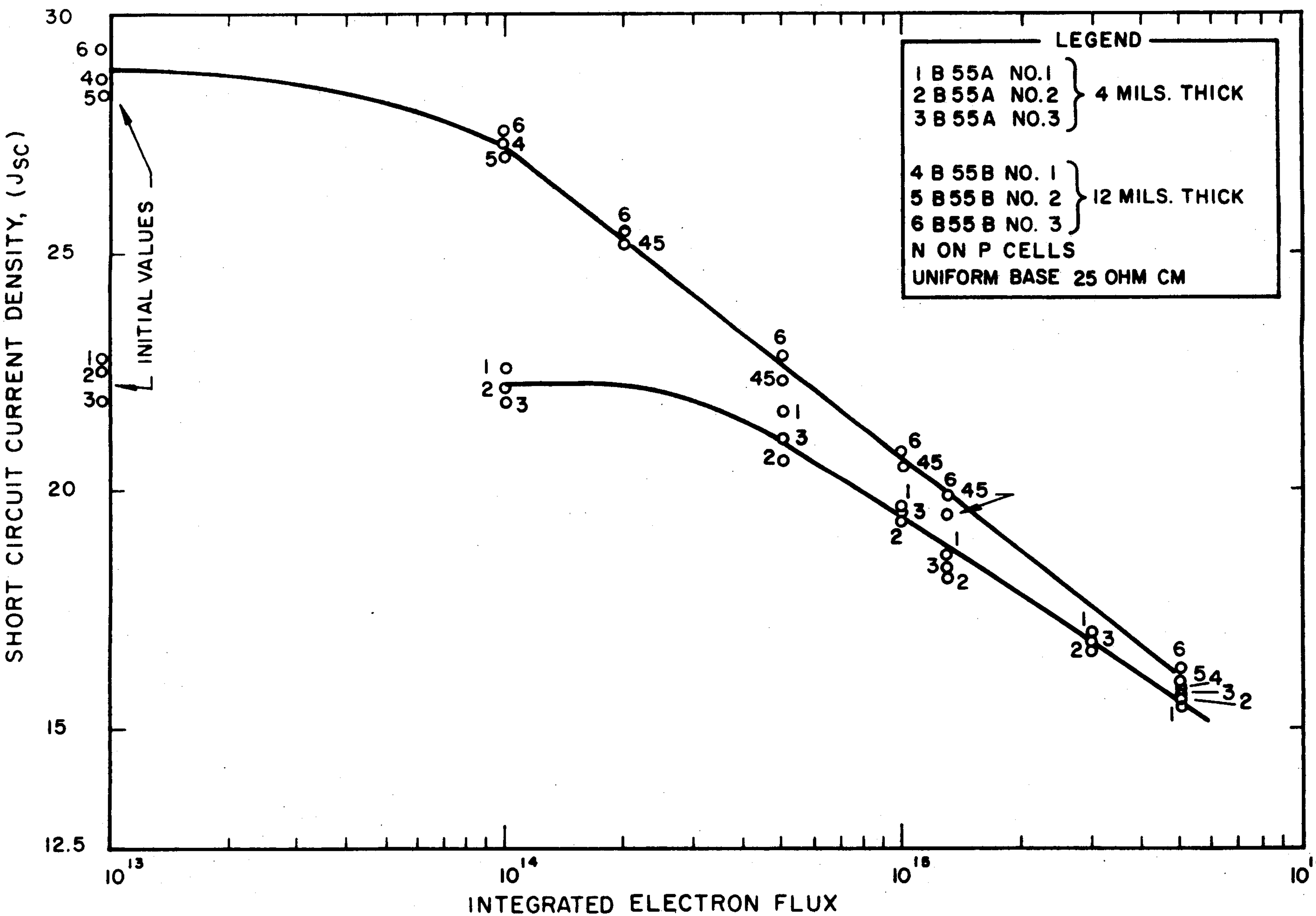


FIG. 14 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

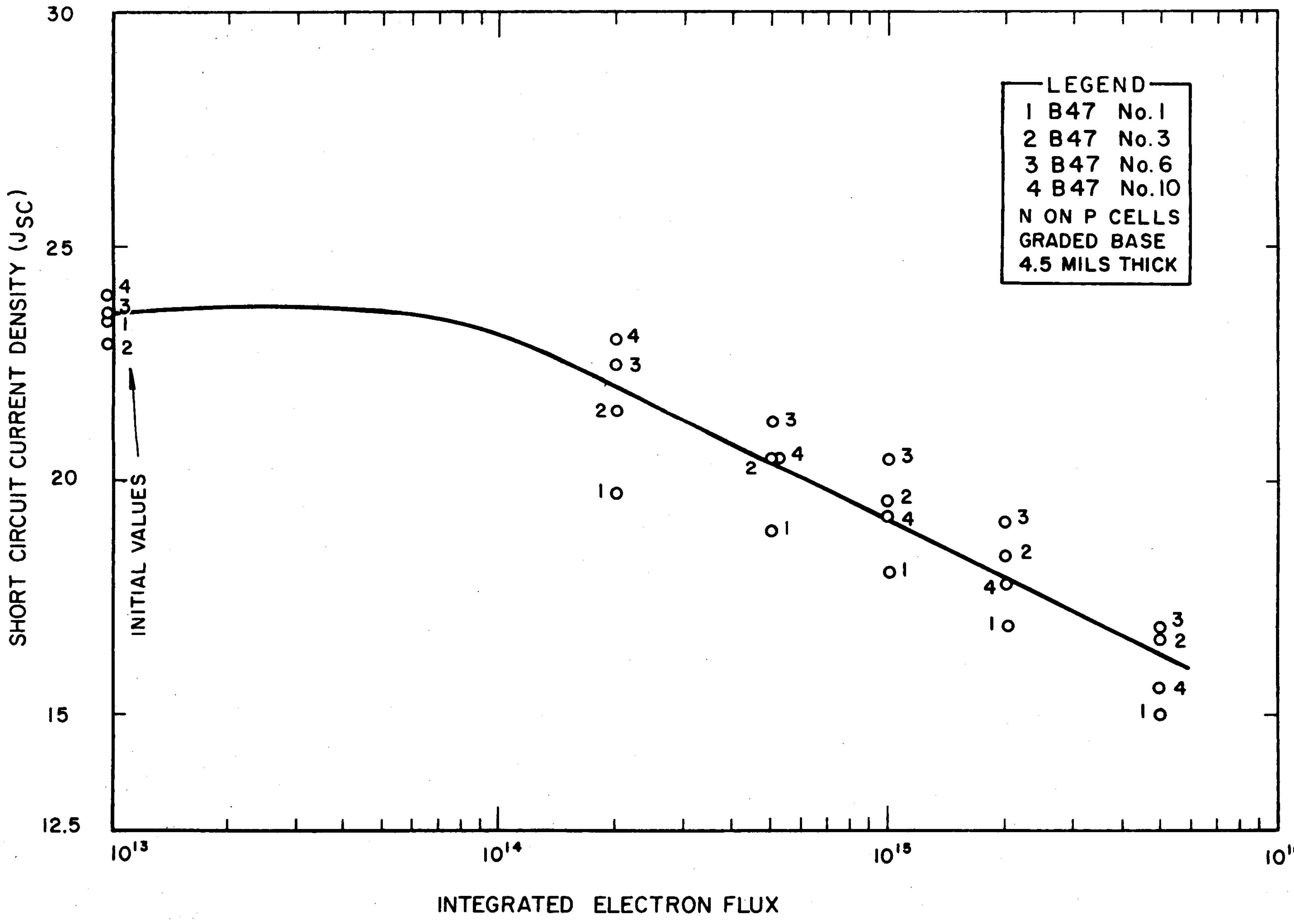


FIG. 16 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

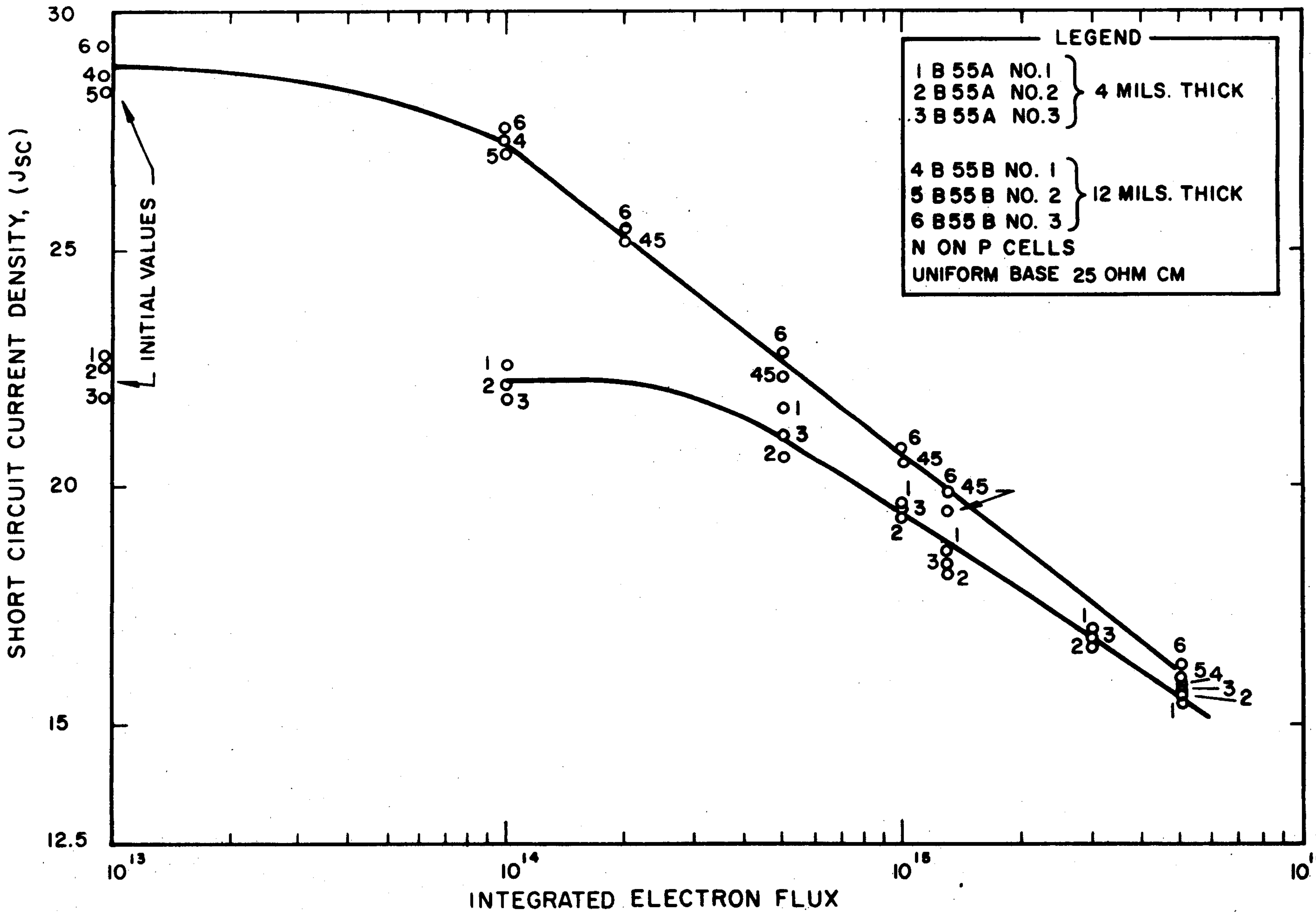


FIG. 14 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

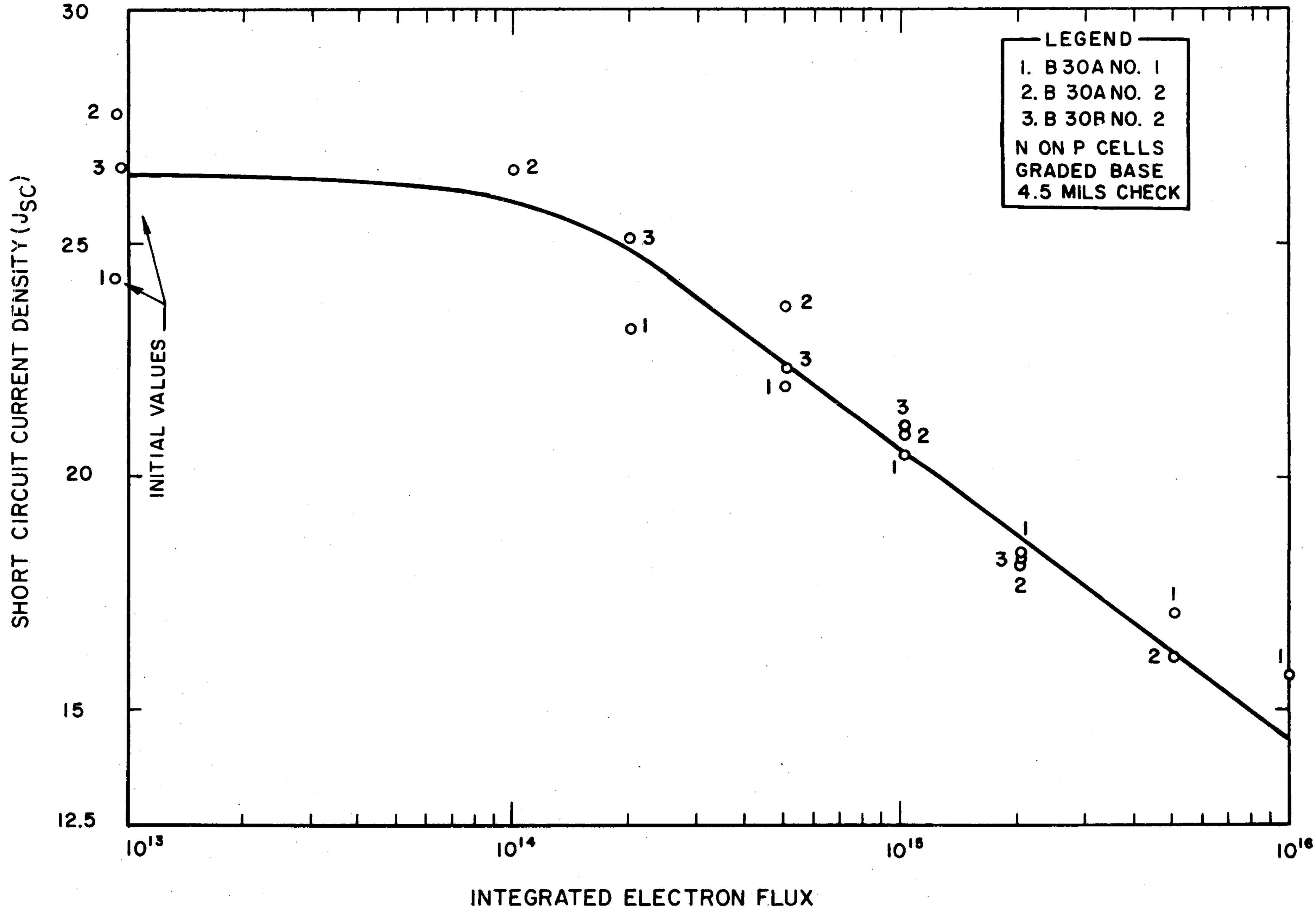


FIG. 17 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

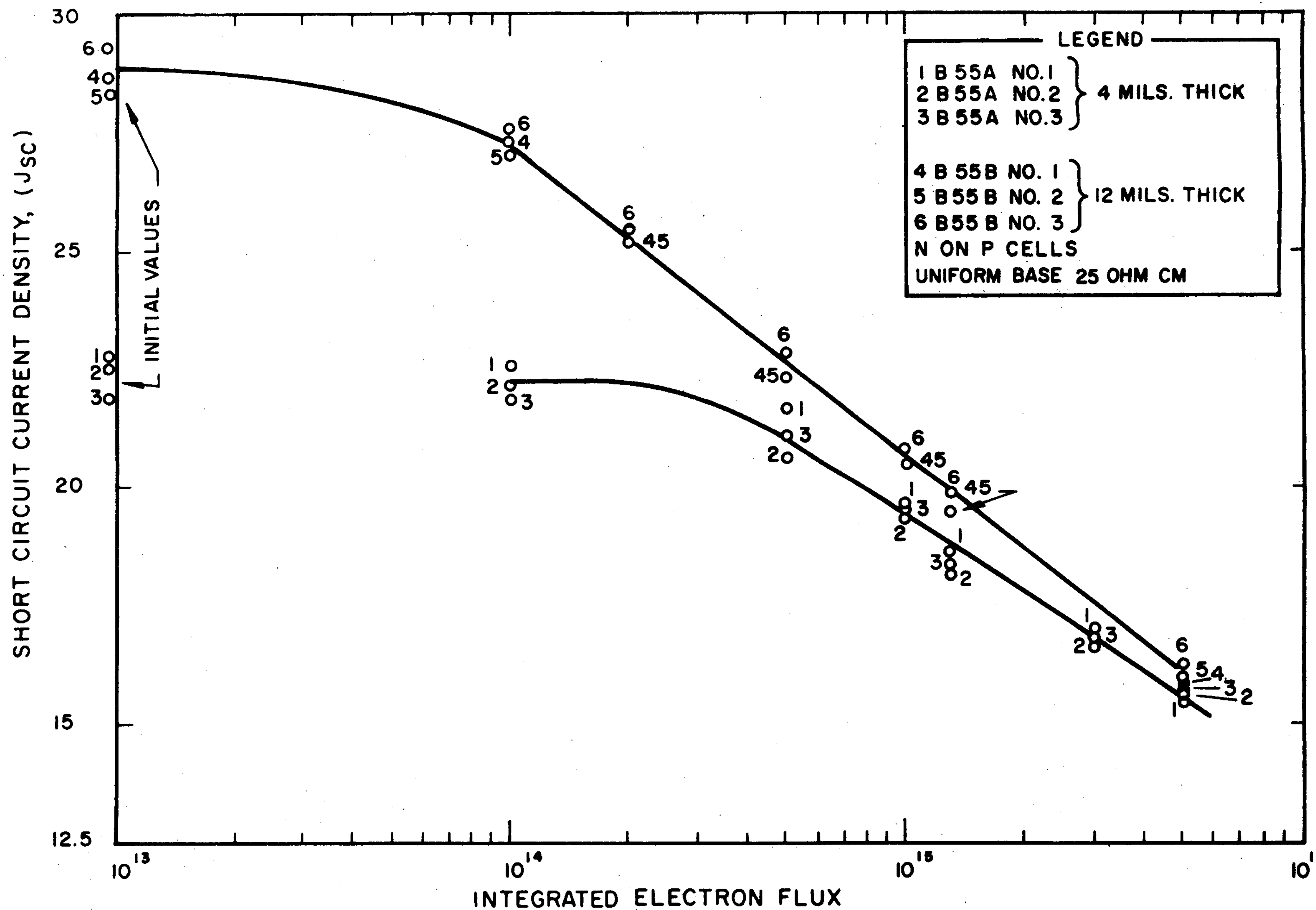


FIG. 14 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

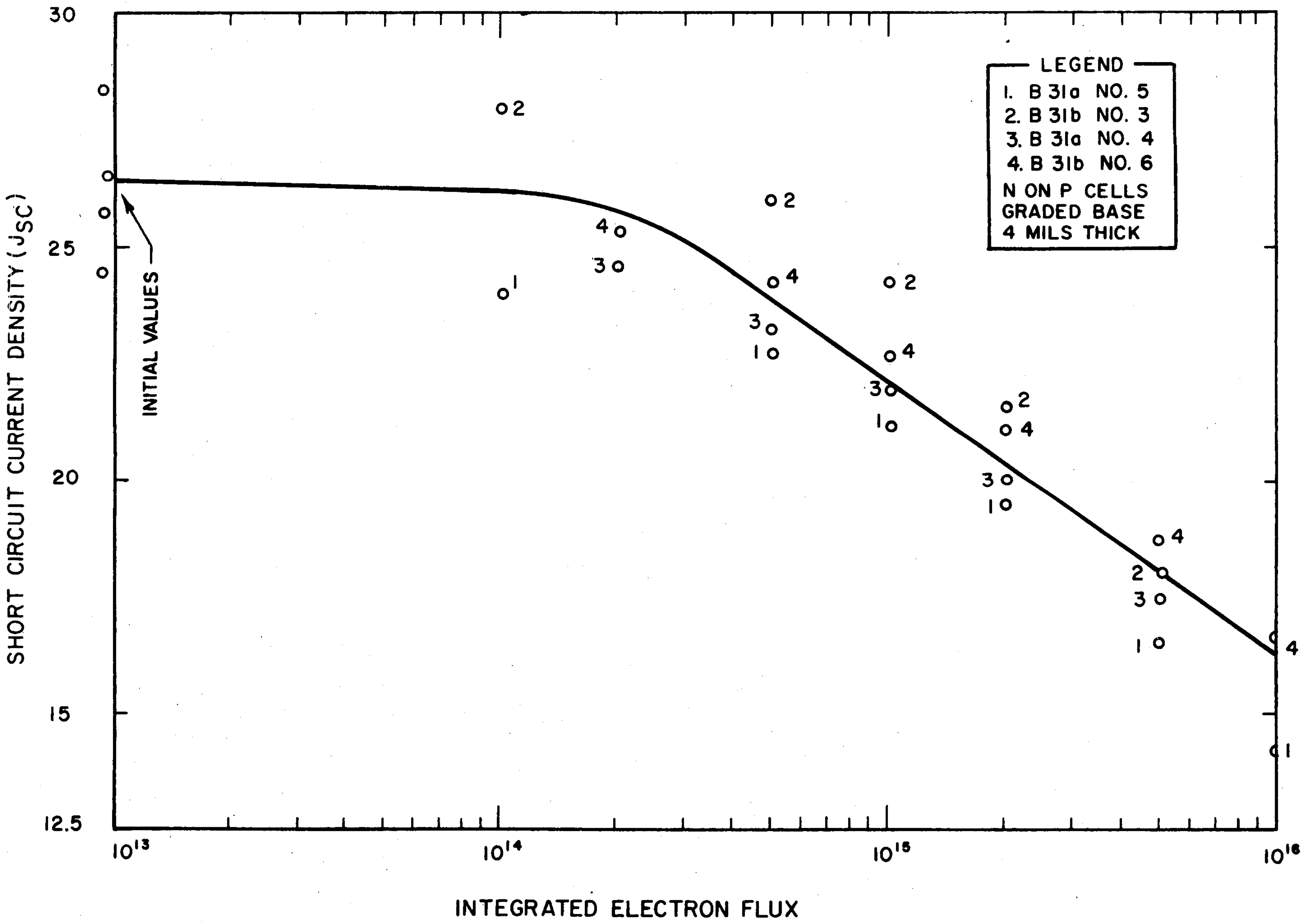


FIG. 18 SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

Figure 14 clearly shows the dangers of evaluating the results in terms of ratios of initial to final short circuit current. If evaluated on this basis, the thin cells would show superior performance. However, we see that by the time the cells have been subjected to a flux of 5×10^{15} electrons per cm^2, the short circuit current of the two groups of cells is almost the same. Comparing the results of the control cells with the graded base cells, we see that in two of the cases for an irradiation level of 5×10^{15}, the performance of the graded base cells was approximately the same as that of the control cells; whereas in the remaining two cases, the short circuit current of the graded base cells was approximately a factor or two higher than that of the control cells.

4.4 Irradiation of P on N

At the technical monitor's suggestion it was decided to irradiate some graded base p on n cells. It was felt that if these showed an improvement in radiation resistance compared with conventional p on n cells, a convincing demonstration of the applicability of the graded base concept of the fabrication of radiation resistant solar cells would result. Three p on n graded base cells were subject to 1 Mev electron radiation in the Van de Graff accelerator at STL. The results of this experiment are shown in Figure 19. The short circuit current of the cells when illuminated by tungsten light is plotted as a function of the integrated electron flux density; the two solid lines shown on this curve represent the performance exhibited by the majority of p on n commercial solar cells and the dotted line indicates the performance of the best p on n commercial cell. It may be observed that even though the graded base cells started off with initially smaller short circuit currents than those of typical commercial cells, these experimental cells exhibited a considerably improved radiation resistance compared with commercial p on n cells.

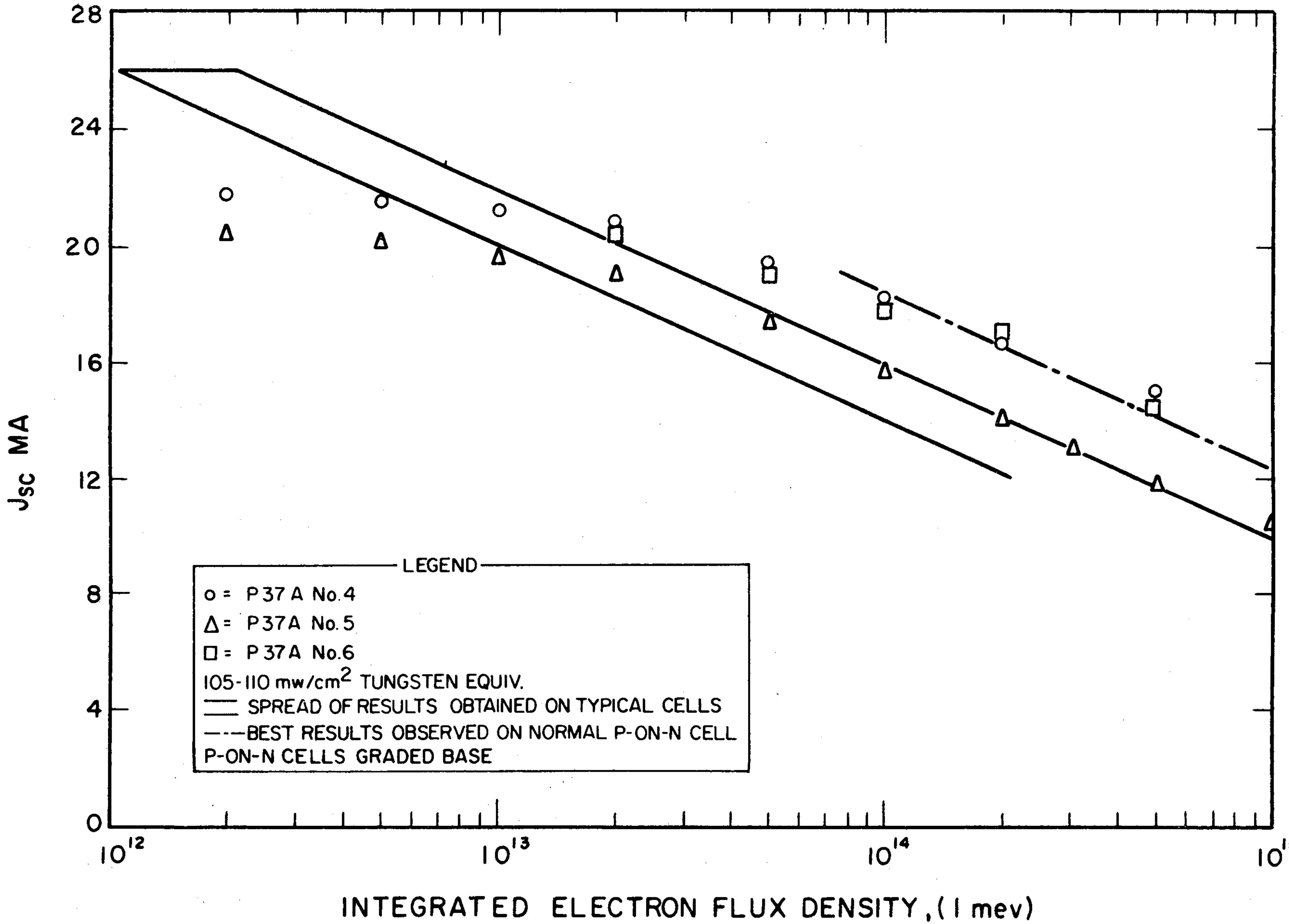


FIG. 19. SHORT CIRCUIT CURRENT DENSITY AS A FUNCTION OF 1 mev ELECTRON FLUX

4.5 Conclusions

The results discussed above indicate that the graded base structure is affecting the transport properties of minority carriers injected into the base region of the cells. The results of the electron irradiation experiments would also indicate that the performance of the cells when subjected to 1 Mev electron bombardment is at least as good and may be superior to that reported on other silicon cells.

5. MEETINGS AND PUBLICATIONS

A meeting was held on August 9th with the technical monitor at Electro-Optical Systems, Inc. Methods of fabrication of graded base cells were demonstrated and discussions took place on the progress of the program and plans were made for future work.

A meeting was held at NASA Headquarters on October 25th. Present was the technical monitor and Mr. J. Mandlekorn of NASA and Dr. M. B. Prince and Mr. S. Kaye of Electro-Optical Systems. At this time an attempt was made to see if any correlation could be obtained between this data and data obtained at other laboratories. The conclusions reached were that due to the different methods of evaluation of the cells after irradiation, it was not possible to obtain a valid comparison of data. In view of this difficulty it was decided to place more emphasis on the theoretical aspects of the work during the last part of this study.

A paper was prepared by S. Kaye, I. Weiman and W. V. Wright describing much of the work which had been done on this project. The paper was presented at the Space Power Systems Conference sponsored by the American Rocket Society which was held in Santa Monica, California from September 25 through 28th. A number of papers of interest in connection with the present work were presented at this conference. Included among these was a paper by R. Fischel of the Applied Physics Laboratory of Johns-Hopkins, describing the effects observed due to the artificial radiation belt produced by the recent high altitude Johnston Island test. The effects of this artificial radiation belt are most noticed by vehicles flying in low altitude equatorial orbits and in this case the damage rate has been increased as much as a hundredfold. A paper by J. M. Denney, STL, entitled "The Effect of Space Environment on the Photovoltaic Cell" dealt mainly with the effect of high energy proton bombardment on solar cells and the ensuing dependence on diffusion length on the incident light level. In addition to these papers a panel discussion was held to discuss the problem of radiation damage on space vehicle power supplies. The results of the panel discussions may be summarized briefly as follows: Despite the increased radiation levels arising from the artificial radiation belt, it is possible to design solar cell power systems for orbital vehicles which will be capable of operating over extended periods of time.

6. FUTURE WORK

1. Fabricate and subject to irradiation such further cells as may be decided upon after discussion with the technical monitor.

2. Conduct a more exact and theoretical study of the mechanism involved in the graded base cell and compare the results of this calculation with those obtained by radiation studies.